HYPERSONIC PROPULSION: PAST AND PRESENT

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SUMMARY

The change of the concept of hypersonic speed with time is in the first place briefly discussed.

The evolution of the hypersonic propulsion is restricted to the history of the ramjets. Considering the abundance of excellent literature on the subject only the most remarkable achievements are commented. Less divulged historical events, such as the propulsion of helicopters by ramjets are discussed with more detail, and special attention is given to the contributions of Spain to supersonic combustion.

The present state of the hypersonic propulsion is commented, reviewing from the literature on the subject some of the most demanding problems facing the propulsion systems of the Aerospace Plane and of the Hypersonic Cruise Aircraft.

1. INTRODUCTION. HYPERSONIC SPEEDS

The history of the hypersonic propulsion systems should begin with the definition of hypersonic speed, because it has changed with time.

Up to the middle 1950's the hypersonic regimen was considered as the flow region at which the linearized theories to study supersonic flows developed by Ackeret[1] and other aerodynamicists, such as Von Kármán and Busemann in the 1920's and 1930's did not longer apply[2].

The approximated theories developed for the study of the hypersonic regime by Hayes, Goldsworthy and others[3], depended not only on the Mach number, but on a geometrical parameter which in turn was a function of the thickness and camber of the profile and of the angle of attack. Therefore, the hypersonic flow region might begin at different Mach numbers.

The same thing happens nowadays, but for very different physical concepts. In the supersonic region when the Mach number increases, several well known phenomena become gradually important; such as curved strong shocks and thin shock layers, entropy layers in blunt bodies, thick and hot boundary layers and the existence of high temperature regions in which the flow is no longer at constant chemical composition, but a reacting flow. When all or some of these phenomena have to be taken into account the flow is considered hypersonic[4].

Therefore, there is not a Mach number defining the change from supersonic to hypersonic, but a transition region. However, for simplicity, it is generally agreed that at Mach number 5 the flow may be considered hypersonic.

The first man-made craft to achieve a hypersonic speed according to the above mentioned definition was a WAC Corporal rocket as a second stage of a German V-2, in White Sands, USA, on 24th February 1949. From that date hypersonic speeds have been reached by the ballistic missiles developed in the 1950's; followed by unmanned and manned spacecrafts reaching orbital speeds and reentry Mach number in the region of 25-27; deep space sondes and even hypersonic piloted aircraft. All these hypersonic vehicles have been powered by rocket motors, due to its relative simplicity, and above all because their performances are practically independent of the outside conditions and they can be fully tested on the ground.

2. AIRBREATHING HYPERSONIC PROPULSION DEVELOPMENT

2.1. INTRODUCTION

The huge potential advantages of the airbreathing engines in terms of fuel consumption in comparison with rocket engines for hypersonic high altitude flights was very early recognized, when jet propulsion was still in its infancy. It is also well known that its development is much more complex, among other things because the performances of the airbreathing engines are fully dependant on the external air flow conditions and because testing at high Mach numbers is extremely difficult. These complicated development problems coupled with the lack of adequated funds for many years* have resulted in that up to date no operational hypersonic airbreathing engines have been developed.

The history of the development of the airbreathing hypersonic propulsion systems, is essentially, the history of the ramjet. In all hypersonic propulsion systems, ramjets are coupled with jet engines and/or rocket motors in a large variety of combinations. However, the ramjet is the essential component of the propulsion systems and it is the only airbreathing engine with the capability of reaching hypersonic speeds. Accordingly, and in order to keep this work within reasonable limits, it will be fundamentally restricted to the evolution of those engines. Special emphasis will be placed on supersonic combustion, the applied technology that gives the ramjet its hypersonic capability.

Many publications have been written on the history of the ramjets. From the early development up to 1955 and excellent history of the ramjet development was published by Avery[5].

In a recent AGARD Conference, Waltrup[6] has published an extensive study on the evolution of ramjets, with special dedication to scramjets, as part of a more extense work on the evolution of hypersonic airbreathing propulsion systems.

Taking into account the excellent and abundant literature on the subject, the part of this work dedicated to the history of the ramjets will be restricted to comment the most important achievements or landmarks, and to detail some less well known contributions, with special emphasis on those of Spain to the supersonic combustion problems.

2.2. EARLY DEVELOPMENTS

Among the many names of early inventors, patents and studies, which are cited in many publications, due credit has to be given to the french R. Lorin[7], who was the first to carry out a study on the potential utilization of ramjets for subsonic applications, recognizing its low efficiency. What makes this work so remarkable it is its pioneering nature and that it was written in 1913, when flight was in a very primitive stage. As a consequence, no practical investigations were carried out.

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*Air breathing engines were left with little money available for research, when most of the resources for propulsion in the United States were devoted for many years to the development of the ICBM and other missiles as well as on space vehicles powered by rocket motors.

Another remarkable achievement for its anticipation was the Fono[5,8] patent of a supersonic ramjet. This patent was granted in Germany in 1928, and in these 1920's it was then when thanks to the works of distinguished aerodynamicists, such as Ackeret, Mach and Prandtl the possibility of supersonic flight was given a real consideration.

Extensive description of these early developments are given in ref. 5 and 9.

2.3. WAR DEVELOPMENTS

The development of the ramjets during the Second World War was carried out mainly in Germany[5,10]. Sänger, of the Air Research Institute at Brunswick, was a leader in the field, and in 1943 he had developed a full scale ramjet which was tested in flight in a DO17Z. His works and the contributions of distinguished scientists and engineers, such as Oswatitsch and Busemann (aerodynamics); Damkölher, Lippisch, Schwalb and Pabst (combustion) and the involvement of some important engine and aircraft companies of Germany (Walter, Focke-Wulf, Heinkel and Messerschmitt), produced the design and test of large units including designs of fighter with full ramjet propulsion[11].

Design and tests were also carried out on artillery projectiles accelerated by ramjets, propulsion of missiles and propulsion of helicopters with tip placed ramjets. It may be pointed out that the design and studies conducted on ramjets in Germany during the War established the foundation of the modern technologies of this propulsion system.

However, due credit must be given to the research and development efforts carried out in the United States. The special relevance were the works of Kantrowitz and Donaldson on supersonic diffusers[12], and the combustion research programme carried out at the Massachusetts Institute of Technology (MIT)[5]. Special mention should be made of R. Marquardt, who founded the Marquardt Company in 1945, which has been since that time one of the leaders in the field.

It is interesting to mention the Bumblebee programme[5], initiated near the end of the war to develop missiles against the Kamikaze attacks of the Japanese fighters. A large number of institutions and companies were involved and the ramjet development programme received a very large impulse.

2.4. POST-WAR DEVELOPMENTS. AIRCRAFTS AND MISSILES

Ramjets development after the war followed several courses. The main ones were the propulsion of aircrafts and missiles; and there existed a limited and not much divulged programme on ramjet propulsion of helicopters and an isolated military laboratory programme on nuclear powered ramjets.

Propulsion of aircrafts by ramjets was a short lived effort, although some remarkable achievements may be mentioned, mainly the Leduc[13] developments and flights in France and the development of flight models of subsonic ramjets by the Marquardt Company in the United States, where a Lockheed F-80 Shooting Star was the first piloted aircraft to fly powered only by ramjets[10].

The development of missiles powered by ramjets were mainly carried out in the United States and in the United Kingdom (not counting the Soviet Union), where surface to air missiles reached operational state.

In the United States the research and development efforts carried out by the John Hopkins University Applied Physics Laboratory, NASA Langley Research Center, NASA Lewis, MIT, the Marquardt Company and others, lead to the development and manufacture of operational ramjets for the missiles Boeing Bomarc (US Army) and Bendix Talos (US Navy) in 1955. This last missile resulted from the Bumblebee programme and was followed some years later by the advance version Typhone.

There are several facts about the research and development efforts carried out in the United Kingdon, mainly by the Rolls Royce company (on that time Bristol Aeroengines) which should be specially pointed out.

This company developed the Thor ramjet for the Bloodhound missile for the RAF, and the Odin ramjet for the Sea Dart missile for the Navy; and the remarkable fact is that the lasts versions of these missiles are still in service. This has provided Rolls Royce with an unique experience on operational reliability of ramjets[14].

Another remarkable fact is the wide range of applications studied by the company in early days, including aircraft propulsion and hypersonic vehicles.

Aside of the abovementioned ramjets developments in the United States and in the United Kingdon, no other operational missiles with ramjet propulsion followed these early efforts; until recent years when the development of integrated rocket-ramjet propulsion systems took place, which gave a very important impulse to the ramjet powered missiles, as it will be later described.

2.5. RAMJETS FOR HELICOPTER PROPULSION

The idea of using air conducted through the blades of the rotor of a helicopter, with or without combustion at the tips, as a propulsion system, is an old one and it is still alive. With these jet powered helicopters the mechanical transmission is eliminated as well as the reaction torque.

Pulse-jets and rockets have been utilized placed on the tips of the rotor blades, with the same purpose, but they were very short lived experiments.

On the other hand, a considerable effort has been carried out to utilize ramjet powered helicopter rotors. Actually, this is the only subsonic applications of ramjets.

The thermal efficiency of a subsonic ramjet is very low, and therefore, the specific fuel consumption of the helicopter is very high. However, a subsonic ramjet is a low cost and low weight machine, which added to the aforementioned advantages made the idea attractive for some special applications.

The original idea is of the german origin. There were some studies and test programmes conducted in Germany during the War, specially in the Focke Wulf Company, although no flying models were developed.

After the War some developments took place in the United States*.

The austrian engineer Doblhoff**, developed the first ramjet powered helicopter: the "Little Henry" for the Douglas Aircraft in 1949. The ramjets had a thrust of 50 N at full tip speed (26 HP total). After a long test programme the Air Force cancelled the project.

The Hiller Company, after rejecting pulse-jets, developed in 1955 the Hornet helicopter, utilizing ramjets. The prototype was initially a great success, and

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*The data on the developments of ramjet powered helicopters in the United States and in the Netherlands have been taken from refs. 15 and 16.

**He was heavily involved during the War developing jet powered helicopters for the Wiener Neustaedter Flugzeugwerke.

a contract was placed on the company to manufacture 15 helicopters for the armed services. The 200 N ramjets were certified by the FAA, but not the helicopter, and therefore, no further orders were received.

The most important achievement on this technology of ramjet powered helicopters was the "Hummingbird" or "Kolibrie", developed by J. Drees for the Netherlandse Helicopter Industrie.

After a research program some prototype helicopters were developed in 1955 powered by two light weight ramjets (9 Kg each). Certification was granted in the Netherlands in 1958 (not in the United States) and a small series of 25 helicopters was manufactured. They were utilized in several countries, mainly for agricultural tasks. Until recient years, some of them were still flying.

In Spain a contribution to the development of ramjet powered helicopters was carried out in the early 1950's.

The german engineer O. Roeder conducted for the Aeronautica Industrial S.A. (AISA) a ground test programme of a rotor powered by ramjets (Fig. 1). The theoretical calculations were carried out at the Instituto Nacional de Técnica Aeroespacial (INTA) by the aeronautical engineer J. de la Cierva, eldest son of the spanish inventor of the autogiro.

A second model (Fig. 2) was developed with foldable ramjets, which constituted a new development to improve autorotation. The programme ended because no funds were allocated to develop a flying model, coinciding with the untimely death of J. de la Cierva.

Ramjets powered helicopters did not succeed for a variety of reasons; mainly the very high fuel consumptions, noise and some autorotation problems.

Modern technologies in the fields of high strength low density materials and on the aerodynamics of supersonic rotors might improve the problem of fuel consumption by increasing rotor tip speeds. However, the problem of noise would have to be alleviated in commercial applications, and there would be the problem of high infrared emission for military applications.

2.6. NUCLEAR POWERED RAMJETS

At the height of the Cold War some research programmes were carried out in the United States directed to the utilization of nuclear energy to power both jet and ramjet engines.

The purpose of the programmes was the development of aircrafts and weapons with the capability of flying for practically unlimited time thus avoiding in this way the possibility of being destroyed by pre-emptive attack on the ground by hostile missiles.

Three experimental programmes were carried out; two on jet engines* and one on ramjets, the Pluto programme.

In the Pluto programme an air cooled nuclear reactor was utilized instead of a combustion chamber. Inlet diffuser and nozzles were of the conventional type.

The idea was to keep ramjets flying at low altitudes over unpopulated areas around the artic regions.

Of the three programmes, the nuclear powered ramjet was the one with less technical problems. After many studies and laboratory tests, the three programmes were cancelled due to their huge political implications.

2.7 SUPERSONIC COMBUSTION. SCRAMJETS DEVELOPMENTS.

From the early development of the ramjets their limitations regarding maximum speed were well known, mainly originated by the compressed air reaching temperatures near the equilibrium values of the hydrogen-air mixtures, at which the only available thrust would be obtained via recombination reactions in the nozzle.

It is generally agreed that the practical limit is around Mach 7. The introduction of supersonic combustion in the ramjets, from there on denominated scramjets, represented a tremendous break in performances, since it gave them

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*One of the programmes (General Electric) was of the open cycle type with a nuclear reactor replacing the combustion chamber. The other programme (Pratt & Whitney) was of the double cycle type, with a sodium loop.

the unique theoretical potential of beeing able to function up to orbital speeds.

As it has already been pointed out in paragraph 2.1, there is abundant literature on the evolution of supersonic combustion and on other all aspects of scramjets. A review of supersonic combustion has been recently published by Barrere[17]. Early developments were reviewed by Ferri [18], and a modern review of the scramjet evolution has been carried out by Waltroup[6], who also published a review on liquid fueled scramjets [19].

Supersonic combustion was initially studied in external flows, directed either to increase lift or to reduce drag. The first practical laboratory demonstration was carried out by Smith and Davies[20] in 1952.

Supersonic combustion was initially achieved in scramjets by means of a shock wave. Diffusive combustion type was introduced by Ferri[21], and it proved to be superior, specially at high Mach numbers.

After these early studies and model tests, in the late 1950's and early 1960's, very important and extensive research programmes on supersonic combustion and on all other aspects of scramjets were conducted. The brunt of the research effort was carried out in the United States; but with relevant contribution in the United Kingdom, France, Germany and Spain (not counting the Soviet Union). In Spain the contributions were of the theoretical type.

One of the main reasons behind that great impulse on the research efforts was the possibility of developing aircrafts with the capability of taking off from normal airports and reaching low orbits, powered only by airbreathing engines: the aerospace plane concept.

The obvious strategic interest of this aerospace plane was the reason why many researchs programmes were sponsored by the armed services.

The first important programme on the aerospace plane concept was conducted by Ferri[21] at the Applied Sciences Laboratory with the collaboration of the Republic company. Subsequently, the USAF launched a major programme: the Aerospace Plane in which collaborated the companies Douglas and Republic. The USAF also sponsored three important programmes on scramjets developments[22], carried out by the Applied Sciences Laboratory, the Marquardt company and the United Aircraft Research Laboratory.

Another major programme was carried out in NASA Langley : The Hypersonic Research Engine, directed to the propulsion of manned vehicles[22]. The US Navy sponsored the programme: the Supersonic Combustion Ramjet Airbreathing Missile, under the direction of the John Hopkins University, Applied Physics Laboratory.

During the same period of time lesser research efforts,but with relevant contributions, were carried out in Western Europe. They are described in detail in refs. 6 and 13, including those carried out in the Soviet Union.

All these important research programmes carried out in the United States and in Europe did not conclude with the development of any operational hypersonic aircraft or missil powered by air breathing engines, and in the 1970's the research efforts decreased considerably and many programmes were cancelled.

It is generally agreed that the reason is that the technological level on that time was not sufficiently advanced to accomplish the formidable task of developing aerospace planes or atmospheric hypersonic vehicles.

2.8 CONTRIBUTIONS IN SPAIN TO SUPERSONIC COMBUSTION

In 1954 a combustion group was constituted at the Instituto Nacional de Técnica Aeroespacial (INTA) of Spain. This group was promoted by the World known aerodynamicist, the late Prof. Von Kármán, and directed for several years by his collaborator on combustion, Prof. and Academician G. Millán*.

The combustion group worked continously for over 20 years under research contracts sponsored by the Air Force Office of Scientific Research**, of the United States.
The combustion group also worked for other US organizations: The Forest Fire Research Service (6 years), the European Office of the Army and the Arnold Engineering Development Center.

When in the late 1950's the US Air Force became highly interested on supersonic combustion, the Spanish combustion group carried out a number of research

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*Von Kármán and Millán gave a course on combustion at La Sorbonne in Paris in 1953. The lecture notes considerably enlarged were published by Millán for the Air Research and Development Command of the USAF in 1954 under the title: Aerothermochemistry.

**Formerly, Office of Aerospace Research of the Air Research and Development Command, of the United States Air Force.

programmes for the aforementioned organization, on several aspects of supersonic combustion and on hydrogen-air flames.

These activities were conducted mainly in the period 1962-1970.

An early work was a study carried out by Pérez del Notario and this author[23] in 1962. Premixed and diffusion laminar hydrogen-air flames were studied with a spherico-symmetrical model, and chemical kinetics was approximated by parametric overall reaction rates, since no overall reactions rates for the hydrogen-air reactions were known. Solution of the problem was obtained by means of approximated integral methods.
The experimental work was carried out by injecting hydrogen in air through porous spheres. With the same experimental equipment the diffusion hydrogen-oxygen flame was studied by injecting oxygen through the same spheres in hydrogen (Fig. 3). There are little or no free convection effects when burning oxidizers in hydrogen and the flame is nearly spherical [24]. (Fig. 4).

On the other hand, when hydrogen is injected in air, free convection exists but the flame is located very close to the sphere surface (Fig. 3) and the spherico-symmetrical model holds.

Several conclusions were obtained[*] and it was shown the advantages of this spherical model in order to obtain from the experimental results information on the main parameters that characterize the flame.

A comprehensive analysis of a supersonic combustion process of the diffusive type was carried out by Da. Riva, Liñán and Fraga [25] in 1964. The model included the study of turbulent mixing. Chemical kinetics non-equilibrium effects were treated with special emphasis on flame extinction for the laminar case, with a tentative extension to the turbulent case. A discussion on the application of the model to the hydrogen-air flame was also included.

Da. Riva[26], carried out in 1966 a study on the internal structure of hydrogen-air diffusion flames by means of singular perturbation methods, utilizing the fact that for large reaction rates the flame is close to chemical equilibrium. The main contribution of the work was the introduction of a very

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*The mathematical possibility of obtaining three stationay solutions with spherical models was analized.

completed chemical kinetics scheme. The study had a direct application to supersonic combustion.

Liñán, Urrutia and Fraga[27], studied chemical kinetics effects in hydrogen-air supersonic combustion of the diffusive type, showing the existence of three regions: the first region close to the injector exit where the flow may be considered frozen for the main reacting species, which is the ignition delay region; a second transition region and a third region far from the injector in which the flow is close to chemical equilibrium.

An ignition delay model was investigated by Da Riva and Urrutia[28] in 1968 in diffusive supersonic combustion under conditions of two-dimensional mixing. It was shown that the temperature of the injector outer wall and to a lesser extent, pressure, injector length and the conditions outside the boundary layer, control the ignition process.

Liñán and Urrutia[29], studied the hydrogen-air flame utilizing singular perturbation methods at temperatures typical of supersonic combustion. A model of eight chemical reactions was utilized.

It was shown the existence of several reaction stages clearly differentiated, which were studied for particular cases obtaining characteristics times and simplified kinetics schemes for each region.

The formation of nitrogen oxides in the hydrogen-air reaction was studied by Sanmartín, Fraga and this author[30*].

A complex chemical kinetics model of 34 reactions was utilized and overall reaction rates were obtained for different temperatures, including those of interest for supersonic combustion.

Fraga, Crespo and this author carried out a review of the principal problems involved in hydrogen combustion, including supersonic combustion[31].

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[*]This work was part of a programme sponsored by the Fundación Juan March of Spain on emission of contaminants in hydrocarbons and hydrogen combustion processes, directed by this author.

Another contribution of the Spanish group to supersonic hydrogen-air combustion problems was the work by Liñán and Crespo[32]. They carried out an asymptotic analysis of unsteady diffusion flames for large activation energy*.

The works uncovered the existence of three regimes, an ignition regime a deflagration regime and a diffusion flame regime. It was pointed out the existence of experimental evidence supporting this complex picture.

This work was continued in 1987 by Jackson and Hussaini[33]. They utilized the same model but including the effect of free shear and Mach number on the ignition regime, on the deflagration regime and on the diffusion flame regimen.

3. PRESENT SITUATION.

3.1 RAMJET POWERED MISSILES.

The development of integrated ramjet-rocket propulsion systems, coupled with advances in technologies, such as on board microcomputers to facilitate control, has given a strong impulse to the design and manufacture of low consumption ramrocket powered tactical missiles for medium and long range missions.

No operational ramjet powered missiles had been developed for many years. Now, the Soviet Union has in operation the well known SA-N family of surface to air missiles, and France [13] has developed the ASME, air to ground missile with nuclear warhead, powered by a liquid fueled ramjet, and the Rustic, with a solid fuel ramjet. In addition, France and Germany are developing in cooperation an antiship missile, the ANS.

All these ramjet powered missiles are only of the supersonic type.

A study to apply scramjets hypersonic propulsion to missiles was carried out by Billig [34].

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*This work was sponsored by the ARO company of the Arnold Engineering Development Center. USA.

3.2 HYPERSONIC AIRBREATHING PROPULSION. CURRENT MANNED PROGRAMMES.

Research and development on hypersonic airbreathing propulsion for manned system is again in a high level of activity and it is the object of political and public interest.

In the United States, the National Aerospace Plane (NASP) is in progress with the goal of developing stage to orbit capability (SSTO) vehicles, based on airbreathing propulsion. Two X-30 manned SSTO hight test vehicles are planned to be developed and another one for ground tests.

The programme is now in the phase of developing technologies, with the main effort on propulsion, and conducting conceptual and preliminary designs.

The programme is being funded by NASA, the Air Force Defense Advanced Research Project Agency (DARPA), the Strategic Defense Initiative and the Navy. 50 organisations and companies are involved and about 6000 people.

Decision to develop the X-30 has been postponed until 1994. A total of $ 3.3 billions will be spent up to that date.

A derivative of the NASP programme would be a hypersonic cruise atmospheric aircraft, the "Orient Express", of which many studies are also in progress.

In Germany there is the Sänger space plane programme and in the UK the Horizontal Take-off and Landing (HOTOL) programme, both vehicles with SSTO capabilities.

In Sänger, airbreating propulsion will be utilized up to Mach numbers of the order of 7; and from there on rocket propulsion will take over. This programme is significantly funded by the German goverment and the prime contractor is the company MBB.

HOTOL is, for the present moment, with little or no funds allocated. It is been announced that it will utilize airbreathing propulsion up to altitudes of 25-26 km and up to Mach numbers of the order of 6 or 7.

There are also hypersonic propulsion activities in France and in Japan, and it has been reported that the Soviet Union is heavily engaged in evaluating aerospace plane concepts and developing the required scramjet technologies.

The reasons behind this renewal of the high level of interest in hypersonic airbreathing powered aircrafts, in addition to commercial reasons, it is that the technology has reached a level at which the development appear as feasible in a near future.

Three technologies are specially significant: Computational Fluid Dynamics (CFD) and the high capability supercomputers; the development of new composite low weight heat resistance materials, and new diagnosis methods to carry out tests, specially the non-intrusive optical methods.

CFD and the new generation of supercomputers are making possible approximated calculations of the complex flow problems in intakes and nozzles, and above all in the combustor. An evaluation of the CFD analysis applied to scramjets is reviewed in ref. 22.

The introduction of the new light weight heat resistance materials in the structure of the aerospace plane, would permit higher Mach numbers at every altitude, making wider and more efficient the so called flight corridor up to orbit[35] (Fig. 5).

These light weight materials would reduce the empty weight of the vehicle and of the power plant, which would decrease the sensitivity factor* to acceptable levels[36].

Finally, non intrusive measurement methods would give more accurate information from tests and better validation of theoretical models[37 38].

3.3 HYPERSONIC PROPULSION SYSTEMS. PRESENT SITUATION.

The propulsion system of the NASP is partially classified. It is known that the main engines will be hydrogen fueled scramjets. No data have been released on the propulsion system from take off up to Mach numbers of the order of 3 or 4.

In addition to the NASP scramjets the US Navy is sponsoring the development of liquid fueled dual combustor scramjets, designed for applications in the range of Mach number 3-7.

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*An error in the empty weight is considerably amplified in the total weight and the same thing occurs with the errors in the estimation of the hydrogen consumption for the mission.

No scramjets developments are reported to being carried out in Western Europe. Airbreathing propulsion in the Sänger will be a combination of jet engines and ramjets. Several possible combinations are being studied by MTU and MBB [39-40].

On the other hand, the propulsion system of the HOTOL has been classified by the UK government, and no information has been released.

Some comments will be included on the extremely difficult problems facing the development of scramjets operating up to or near to orbital speeds.

A review of these and other hypersonic propulsion problems has been carried out by Cheng [41]. In this analysis it is pointed out that the boundary control in the diffuser, and the nozzles problems although difficult will be solved and that the main difficulties lie in the combustor.

In a flight corridor that a space plane will have to follow such as that shown on Fig. 5, the spacecraft will follow a trajectory of maximum admissible dynamic pressure in order to optimize combustion. This maximum pressure, dictated by the airframe, is estimated in ref. 35 to be of the order of six times the value admitted in actual commercial subsonic transports.

At a certain Mach number, (12-13) the aircraft will have to climb faster, in order to avoid excessive heating of the heat shield of the structure (Fig. 5). Then, the very rapid exponential decrease of the atmospheric density could not be compensated with dynamic pressure, and combustion might not be possible. Cheng[41], believes that with present scramjets combustion systems, they will not be able to operate at altitudes higher than 60 km. Hydrogen reaction rates are of second order, and then proportional to the square of density, which originates that thrust falls rapidly with height. He proposes to utilize at high altitude a catalytic first order reaction in which oxygen will react on a molecular layer of hydrogen absorbed on platinum or other metals. The reaction rate will only be proportional to the density and the thrust of the scramjet will decrease much slower with height and it would be much easier to produce a positive thrust margin over drag at very high altitudes.

On the other hand, Waltrup [6], proposes a scramjet utilizing different types of injector systems, and the injection of hot combustion products and fuel, which might be produced by the exhaust of a hydrogen rich rocket exhaust for high altitude operation.

A simple solution would be to utilize rocket propulsion in the last part of the flight path, which would be needed in all cases in orbit for manoeuvres and during re-entry. We would like to remark that an important feature of the space plane would be its capability to reach high Mach numbers at relatively low altitudes, because the difference in potential energy between orbit level (~ 150 km.) and a height of 60 km is less than two orders of magnitude in comparison with the kinetic energy of orbital speeds.

Finally, we would like to comment on the hypersonic propulsion systems of the "Orient Express".

They are very different proposals for that propulsion system, which depend, to some extent, on the cruise conditions selected.

It has been mentioned that scramjets would be an ideal power plant for cruise Mach numbers of the order of 5-6 with cruise altitudes of about 40 km [41]. On the other hand, Schwab and Hewit[42], estimated that a hypersonic aircraft would require to have a subsonic speed capability over long distances in the event of engine malfunction. In consequence, they propose a dual mode turbojet-ramjet power plant, carrying out several optimization studies for Mach numbers ranging between 4 and 6.

There are doubts about if this type of aircraft will ever be constructed, in addition or substituting a Mach 2-3 supersonic transport. There is the old known problem of the maximum admissible acceleration for ordinary passengers, estimated to be of the order of 0.2g[42-43], which coupled with the time lost on the ground makes imperative long ranges (Fig. 6). Hydrogen must be utilized, and in addition to all technical problems of this type of aricraft, it would have to be included the logistic problem of having storage and fueling facilities of liquid hydrogen in most major airports throught the World.

On the other hand, utilization of hydrogen would not be a major problem in selected aerodromes for the aerospace plane operation.

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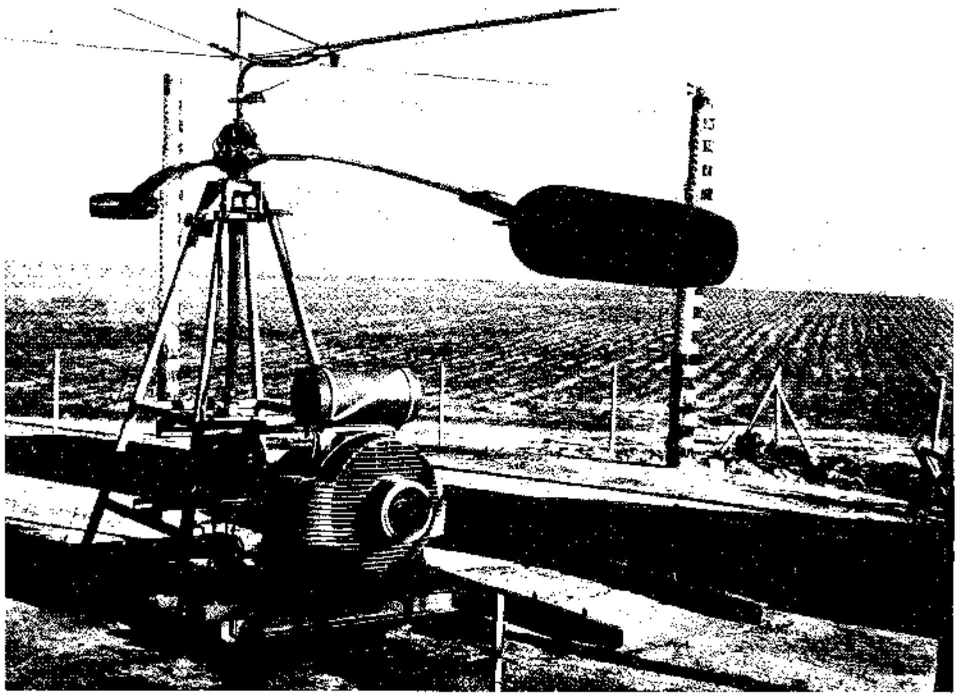


FIG. 1 GROUND TEST OF THE AISA RAMJET POWERED HELYCOPTER ROTOR.

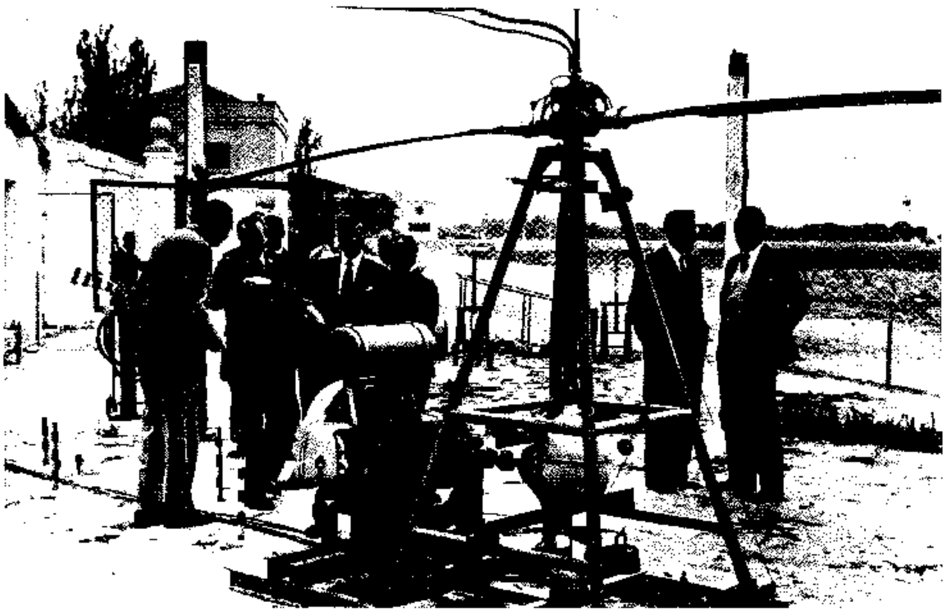
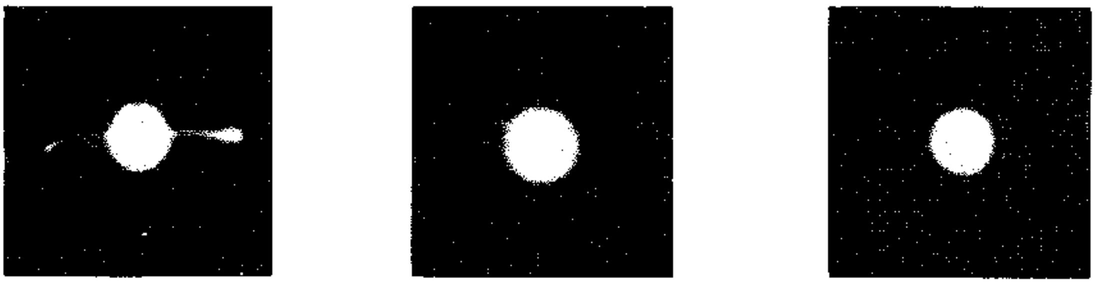


FIG. 2 AISA HELYCOPTER ROTOR WITH FOLDABLE RAMJETS.

FIG. 3 OXYGEN BURNING IN HYDROGEN (LEFT) AND HYDROGEN BURNING IN AIR (RIGHT).



T = 0 SEC. T = $\frac{1}{12}$ SEC. T = $\frac{2}{12}$ SEC.

FIG. 4 NITRIC ACID DROPLETS BURNING IN HYDROGEN.

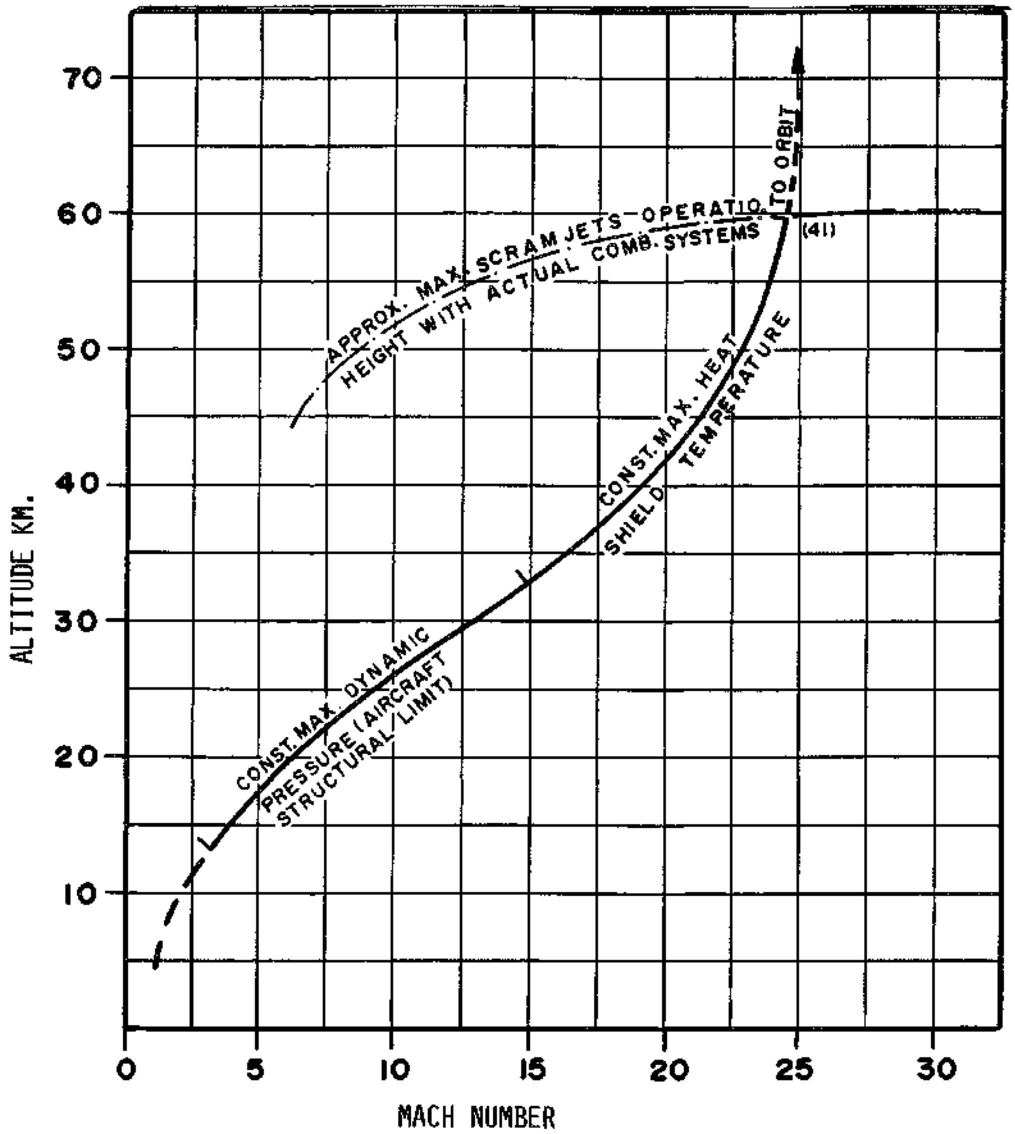


FIG. 5 APPROXIMATED FLIGHT PATH OF AN AIRBREATHING SINGLE STAGE TO ORBIT VEHICLE.

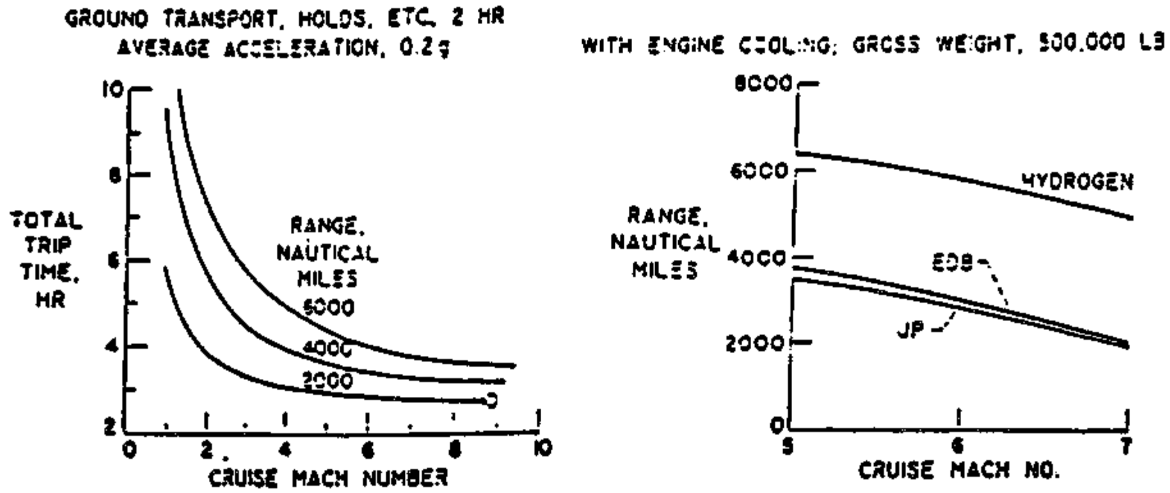


FIG. 6 INFLUENCE OF RANGE (LEFT) AND TYPE OF FUEL IN A HYPERSONIC CRUISE AIRCRAFT (REPRODUCED FROM REF. 43.)